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# The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil

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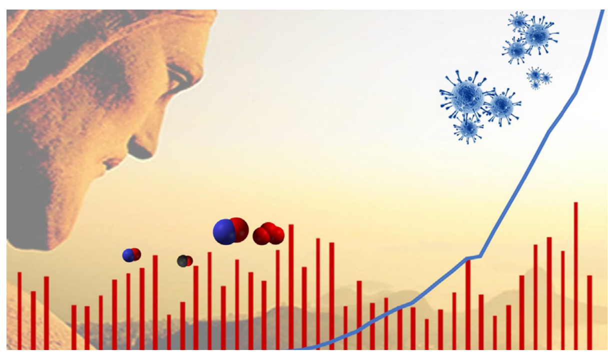
## HIGHLIGHTS

- CO levels showed the most significant reductions during the partial lockdown.
- $NO_2$ decreased in a lower extent, due to industrial and diesel input.
- $PM_{10}$ levels were only reduced during the first partial lockout week.
- Ozone increased due to the decrease in nitrogen oxides level in a VOC-controlled scenario.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The first COVID-19 case in Brazil was confirmed on February 25, 2020. On March 16, the state's governor declared public health emergency in the city of Rio de Janeiro and partial lockdown measures came into force a week later. The main goal of this work is to discuss the impact of the measures on the air quality of the city by comparing the particulate matter, carbon monoxide, nitrogen dioxide and ozone concentrations determined during the partial lockdown with values obtained in the same period of 2019 and also with the weeks prior to the virus outbreak. Concentrations varied with substantial differences among pollutants and also among the three studied monitoring stations. CO levels showed the most significant reductions (30.3–48.5%) since they were related to light-duty vehicular emissions. $NO_2$ also showed reductions while $PM_{10}$ levels were only reduced in the first lockdown week. In April, an increase in vehicular flux and movement of people was observed mainly as a consequence of the lack of consensus about the importance and need of social distancing and lockdown. Ozone concentrations increased probably due to the decrease in nitrogen oxides level. When comparing with the same period of 2019, $NO_2$ and CO median values were 24.1–32.9 and 37.0–43.6% lower. Meteorological interferences, mainly the transport of pollutants from the industrial areas might have also impacted the results.



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## 1. Introduction

On December 31, 2019, China alerted the World Health Organization (WHO) of several cases of unusual pneumonia in Wuhan, an 11 million people city in the central Hubei Province. On January 7, 2020, the identification of a new virus, named SARS-CoV-2, was announced (WHO, 2020a). The disease, known as COVID-19, produces mild symptoms in most people, but can also lead to severe respiratory illness. On January 23, authorities have quarantined the city of Wuhan and, by the end of January, authorities had enforced restrictions in at least fifteen additional cities in Hubei Province. Cases were recorded in every province-level subdivision in China and, in a few weeks, the virus had spread to dozens of other countries in Asia. The United States reported the first coronavirus case on January 20, in the Washington State, and, on January 24, the first cases were reported in Europe (Spain, France and Italy) (Hopkins, 2020). Latin American was free of the virus until February. The first case confirmed by the Brazilian Ministry of Health (on February 25) was a 61-years old man who had travelled to Lombardy, northern of Italy (Rodriguez-Morales et al., 2020). On March 5, the Argentinian Ministry of Health reported the first coronavirus case, a 43-years old man who has also visited Italy (Argentina, 2020). Since then, the virus has spread all over the world: in Africa, Asia, America, Europe and Oceania (Hopkins, 2020).

On March 12, 2020, there were more than 118,000 cases in 114 countries and the WHO announced that COVID-19 could be characterized as a pandemic (WHO, 2020b). On April 2, 1 million cases and more than 52,000 deaths were reported, affecting 204 countries and territories around the world. Fifteen days later, the number of cases had risen to more than 2 million (Hopkins, 2020). As the cases spread, most of the countries adopted restrictions to the transportation, commerce and cultural activities, schools and universities were closed and exams were cancelled, and social distancing was imposed.

Brazil declared COVID-19 a public health emergency on February 3 (Croda et al., 2020) and São Paulo and Rio de Janeiro were the first states to step up coronavirus restrictions. On March 16, Rio de Janeiro state's governor declared public health emergency and determined that schools and universities should remain closed, and theaters, cinemas and other public events should be cancelled, work at home would be implemented when possible and gatherings should be avoided. On March 19, a new decree determined that bars, restaurants, beaches, shopping centers and commerce in general (except for food and medicines) should be shut from March 21. Public transport within the city was limited as well as part of the passenger's transport within states. Industrial activities were not suspended, as well as all activities related to health and basic services (DOERJ, 2020). Similar restrictions were adopted in the state of São Paulo.

The outbreak of the coronavirus led to the emptying of streets and public spaces whether by the partial lockdown or by personal responses. During the first quarantine week, in Rio de Janeiro, public transport had a reduction of approximately 50% and private vehicles were significantly reduced (Cyberlab, 2020). The containment measures had a huge impact in the daily life of the citizens, but they also had a positive impact on air quality (Saadat et al., 2020). Satellite images recorded in March and April 2020 showed a clear decrease in particulate matter in the metropolitan areas of São Paulo and Rio de Janeiro. Pollutant concentrations depend on emissions, but also on meteorological conditions, transport, deposition and atmospheric chemistry, so a direct relation between satellite images for a single day and emissions cannot be done. Anyway, the same results had been observed in China, Italy, Spain, France and other areas of the world (Copernicus, 2020; NASA, 2020; Muhammad et al., 2020).

As an example, in Fig. S1 (Supplementary material), satellite images obtained on March 23 (2018, 2019 and 2020) and on March 16, March 23 and April 06, 2020 (before the lockdown, on the first lockdown day and during the lockdown, respectively) are displayed (Earth, 2020). These data obtained by the CAMS/Copernicus/European Commission + ECMWF suggested a decrease of fine particulate matter ($PM_{2.5}$).

Since the relationship between local emissions and environmental concentrations is not linear and vary for different areas of a city, results of individual air quality monitoring stations may not show the same reductions.

The main goal of this work is to discuss the impact of COVID-19 pandemic on the air quality of the city of Rio de Janeiro comparing the particulate matter, carbon monoxide, nitrogen dioxide and ozone concentrations determined during the partial lockdown with values obtained in the same period of 2019 and also with the weeks prior to the virus outbreak.

## 2. Material and methods

### 2.1. Studied area

Rio de Janeiro is a coastal city located on the western shore of Guanabara bay. The city is the capital of the state of Rio de Janeiro and is part of the Metropolitan Region of Rio de Janeiro (MRRJ), the second largest urban center in Brazil, with approximately 12 million inhabitants. The city of Rio de Janeiro has approximately 6.5 million people, with 70.7% of its territory urbanized and large areas (more than 30%) covered with the remaining tropical rainforest vegetation (Braga et al., 2019; IBGE, 2020). The city is divided by the Tijuca Massif in the southern and northern regions. The south, a typical urban area with residential and commercial buildings and predominance of vehicular emission sources, receives winds from the Atlantic Ocean. The north of the city receives air masses from the main industries in the MRRJ: metallurgical and steel industries in the western zone of the city of Rio de Janeiro (Santa Cruz and Campo Grande districts), pharmaceutical, chemical, plastic and metallurgical industries in the northern area (cities of Belford Roxo and Nova Iguacú) and the city of Duque de Caxias (northeastern area), with more than 800 industries in several sectors, such as chemistry, petrochemistry, oil refining, fuel storage, power generation, gas production, plastic and metallurgy (Dantas et al., 2020).

In this study three Districts, shown in Fig. 1, located in the northern and western area were analyzed: Irajá, Bangu and Tijuca. These locations were selected because they are representative of the city, with different characteristics, and have been characterized in previous studies (Dantas et al., 2019, 2020; Mendes et al., 2020; Silva et al., 2018). The Districts of Irajá and Bangu frequently show ozone pollution episodes and are located in an area which receives the air transported from the industrial and petrochemical districts. In Irajá, the wind rose shows the predominant winds from the east and northeast and from the west. In Bangu predominant winds are from the east and west. Tijuca, also located in the northern area, near the Tijuca Forest mountains (Tijuca Massif) predominantly receives weak mountain breezes from the south and pollutants due to local vehicular emissions. These locations have been previously described by Dantas et al. (2020) and the main characteristics are briefly described in Table 1.

### 2.2. Experimental data

Air quality data available for the city of Rio de Janeiro is very limited, especially regarding hydrocarbons (HC) and nitrogen oxides ($NO_x$). During the studied period, data was obtained by the automatic monitoring stations of the Municipal Department of the Environment (SMAC), using standard methods and equipment according to Brazilian legislation (CONAMA, 1990, 2018). Ecotech analyzers (Melbourne, Australia) were used to monitor nitrogen dioxide-$NO_2$ (Serinus® 40 model), carbon monoxide-CO (Serinus® 30 model), ozone-$O_3$ (EC 9810 and Serinus® 10 model), total hydrocarbons (THC) and non-methane hydrocarbons-NMHC (Synspec


**Fig. 1.** Localization of the monitoring stations in districts of Irajá (ID), Bangu (BD) and Tijuca (TD). Wind roses and photographs of the locations are also show as well as the industrial areas of Campo Grande (CG, western), Santa Cruz (SC, west), Belford Roxo (BR, northern), Nova Iguaçu (NI, northern) and Duque de Caxias (DC, northeastern).

Alpha 115 model). Particulate matter with diameter small or equal to 10 μm ($PM_{10}$) was determined with a Met One BAM-1020 Continuous Particulate Monitor (Washington, USA). The concentrations of $NO_2$, CO, $O_3$ and NMHC were obtained at 10-minute intervals and $PM_{10}$ at 1-hour intervals. $NO_2$ and NMHC were not determined at the Tijuca monitoring station, while CO was not determined at Irajá station during the studied period.

Meteorological parameters (temperature, relative humidity, solar radiation, speed and wind direction) were also determined in the three monitoring stations. In this study, the impact of these parameters on air quality was not quantitatively evaluated, but data were used for a qualitative interpretation of pollutant concentrations.

Experimental data obtained by the monitoring stations were initially analyzed to identify spurious data and values were organized in spread sheets as 1-hour means. For the comparison of the results obtained in different days, medians were used instead of mean and standard deviation values, because data are not necessarily parametric. For the same reason, results are presented as boxplots. Statistical analysis was performed using free software (R, 2020) and standard methods.

## 3. Results and discussion

Experimental results were obtained from March 2, 2020 to April 16, 2020 at the monitoring stations of Irajá ($PM_{10}$, $NO_2$, $O_3$, THC and NMHC), Bangu ($PM_{10}$, $NO_2$, CO, $O_3$, THC and NMHC) and Tijuca ($PM_{10}$, CO and $O_3$). The obtained results are shown in Figs. 2–4, respectively, for Irajá, Bangu and Tijuca. For each day, 1-hour means, from 6:30 to 18:30 h (local time BRT), were calculated and plotted as boxplots. Results covering the whole day (day and night hours) are shown in the Supplementary material section. Data obtained in January and February 2020 were not considered because, during those months, pollutant concentrations are in general impacted by the high flux of tourists due to summer holidays and the celebration of Carnival. Also, during February 2020, the rainfalls (276.1 mm) were 155% higher than the historical mean in 1997–2019 (Alerta Rio, 2020), affecting the pollutant

**Table 1**
Description of the studied areas in the city of Rio de Janeiro (Tsuruta et al., 2017; Dantas et al., 2020).

| District | Coordinates | Population | Characteristics |
|---|---|---|---|
| Irajá | 22°49′53.71″S 43°19′ 36.71″W | 461,000 | The monitoring station is located in Nossa Senhora da Apresentação Square, approximately 100 m away from two main streets with high flux of light and heavy-duty vehicles. It is also close to Irajá Cemetery, a taxi station and a supermarket with high flux of trucks. The square includes leisure and open walking areas and hosts cultural events. |
| Bangu | 22°53′16.53″S 43°28′ 15.91″W | 413,000 | The monitoring station is located in an area with moderate vehicular flow, approximately 20 km from the Atlantic coast and surrounded by the Gericino (altitude 970 m) and Pedra Branca (altitude 1020 m) mountains, which are natural barriers for air circulation. This urban region is considered one of the Rio de Janeiro districts with the highest temperatures. |
| Tijuca | 22°55′30.07″S 43°13′ 57.33″W | 165,000 | The monitoring station is located at Saens Peña Square, approximately 100 m from Avenue Conde de Bonfim, a main street with high flow of light-duty vehicles and buses and 200 m away from the mountainous area of Sumare which is covered by tropical rainforest species. The area characterized by commercial activities and a high flow of vehicles and people because of a terminal subway station, as well as many restaurants, bars and leisure activities. |

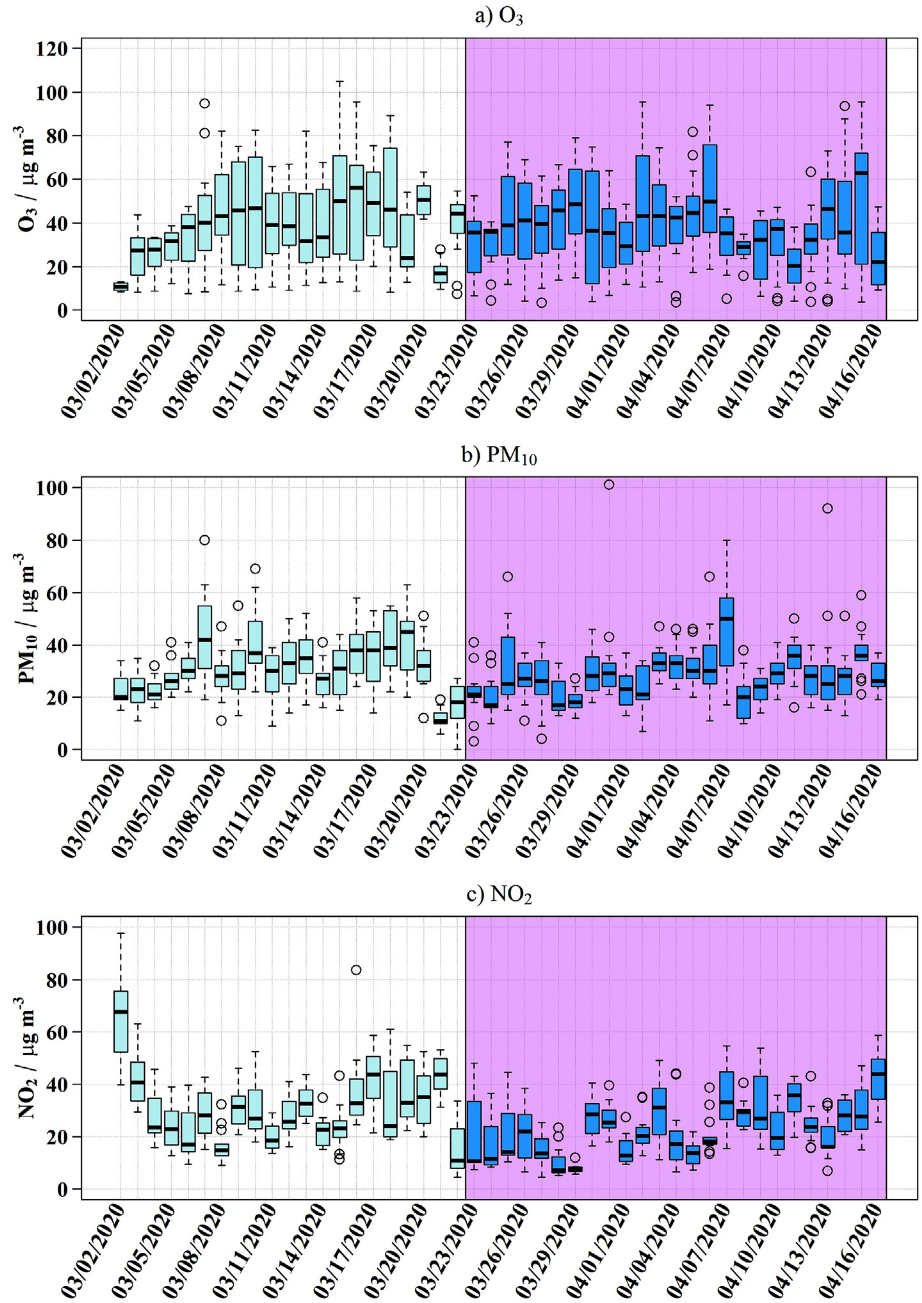


**Fig. 2.** Concentration values (µg m$^{-3}$) determined at Irajá monitoring station from March 2 to April 16, 2020. a) $O_3$; b) $PM_{10}$; c) $NO_2$. The lockdown began on March 23, 2020.

concentrations. All the monitoring stations operated by SMAC are located within the urban area, unfortunately no background stations are available to use as a reference.

In Figs. 2–4, daily concentrations ($O_3$, $PM_{10}$, $NO_2$ and CO) are shown as boxplots. THC and NMHC concentrations, determined in Irajá and Bangu, are show in the Supplementary material section (Figs. S2 and S3). As previously described, the most important partial lockdown procedures started on March 21–23 (Saturday–Monday). Then, the period from March 23 to April 16 was highlighted in a darker color. The spread of the data is typical of these locations as have been shown in previous studies (Tsuruta et al., 2017; Dantas et al., 2019; Geraldino et al., 2020).

As a general trend, concentrations varied with substantial differences among pollutants and also among the monitoring stations. In general, primary pollutant concentrations showed a decrease in the first days of the lockdown. The differences observed between them can be explained considering the fleet characteristics in Rio de Janeiro. According to the last emission inventory for the MRRJ, mobile emissions account for 98, 67.3, 66.5 and 42.3% of total emissions of CO, HC, $NO_x$ and $PM_{10}$, respectively (INEA, 2016). Mean values for Brazil, estimated in the last national inventory of vehicular emission, showed that 47 and 46% of CO and NMHC, respectively, are emitted by light-duty vehicles (LDV). Motorcycles also contribute with a high fraction (34 and 25% of CO and NMHC). Heavy-duty vehicles (trucks and buses), fueled by diesel, contribute to 91 and 96% of $NO_x$ and particulate matter emitted by vehicular sources, respectively (NEI, 2014). During the partial lockdown, trucks continue to run since industrial and construction activities were maintained as well as the transport of food and cargo in general. The fleet of buses was partially reduced while passengers' cars circulations had a 70–80% decrease in the first lockdown week (03/23–03/29) and then raised to approximately 50% (Fiocruz, 2020). Then, a

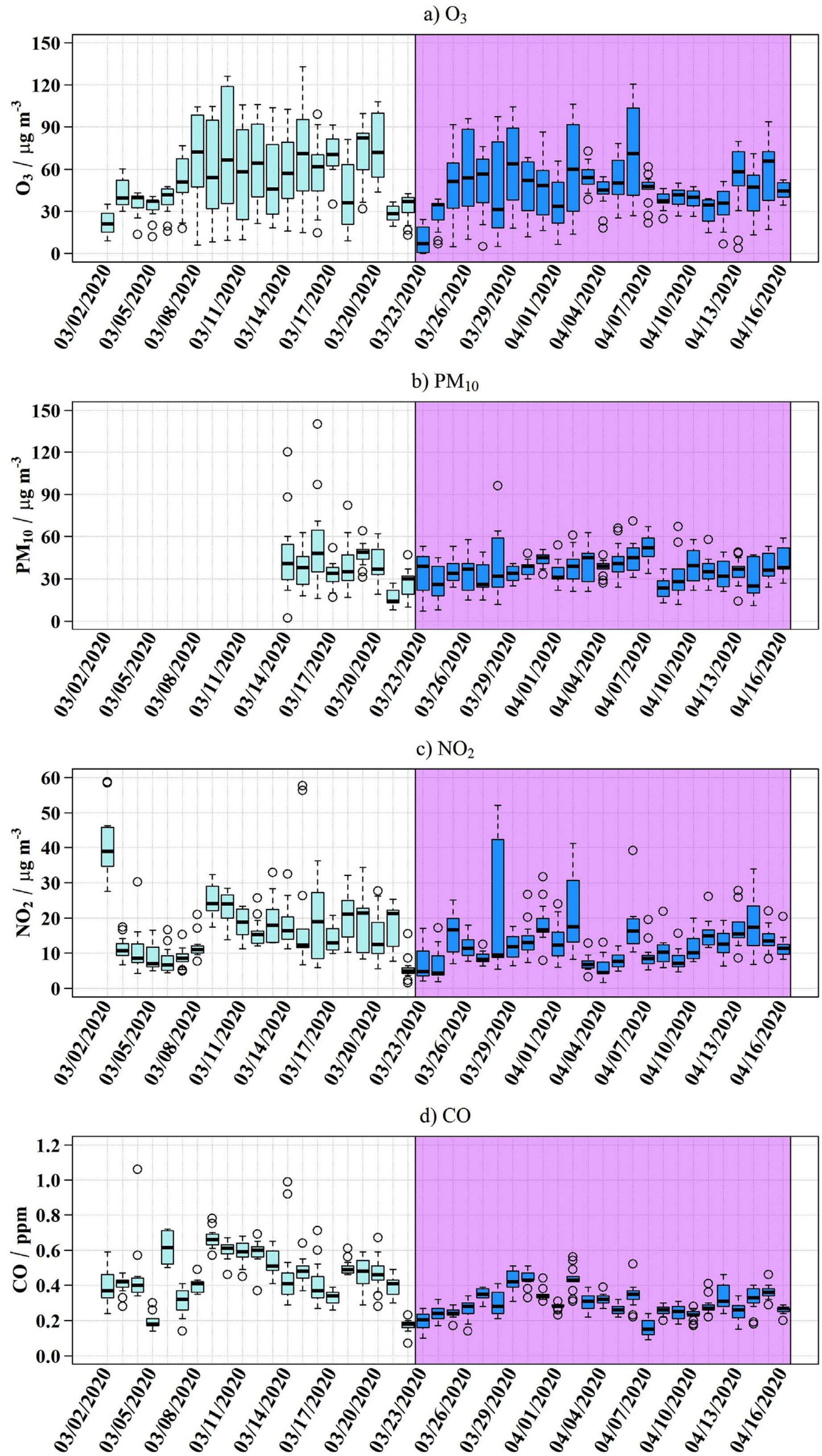


**Fig. 3.** Concentration values determined at Bangu monitoring station from March 2 to April 16, 2020. a) $O_3$ (μg m$^{-3}$); b) $PM_{10}$ (μg m$^{-3}$); c) $NO_2$ (μg m$^{-3}$); d) CO (ppm). The lockdown began on March 23, 2020.

higher decrease in CO and NMHC should be expected, mainly for the period of 03/23/2020 to 03/29/2020, as will be discussed later. Ozone concentrations, the main secondary pollutant in Rio de Janeiro, markedly increased, mainly in Tijuca and Irajá, as expected considering previous results obtained during a ten-day truck driver strike (Dantas et al., 2019).

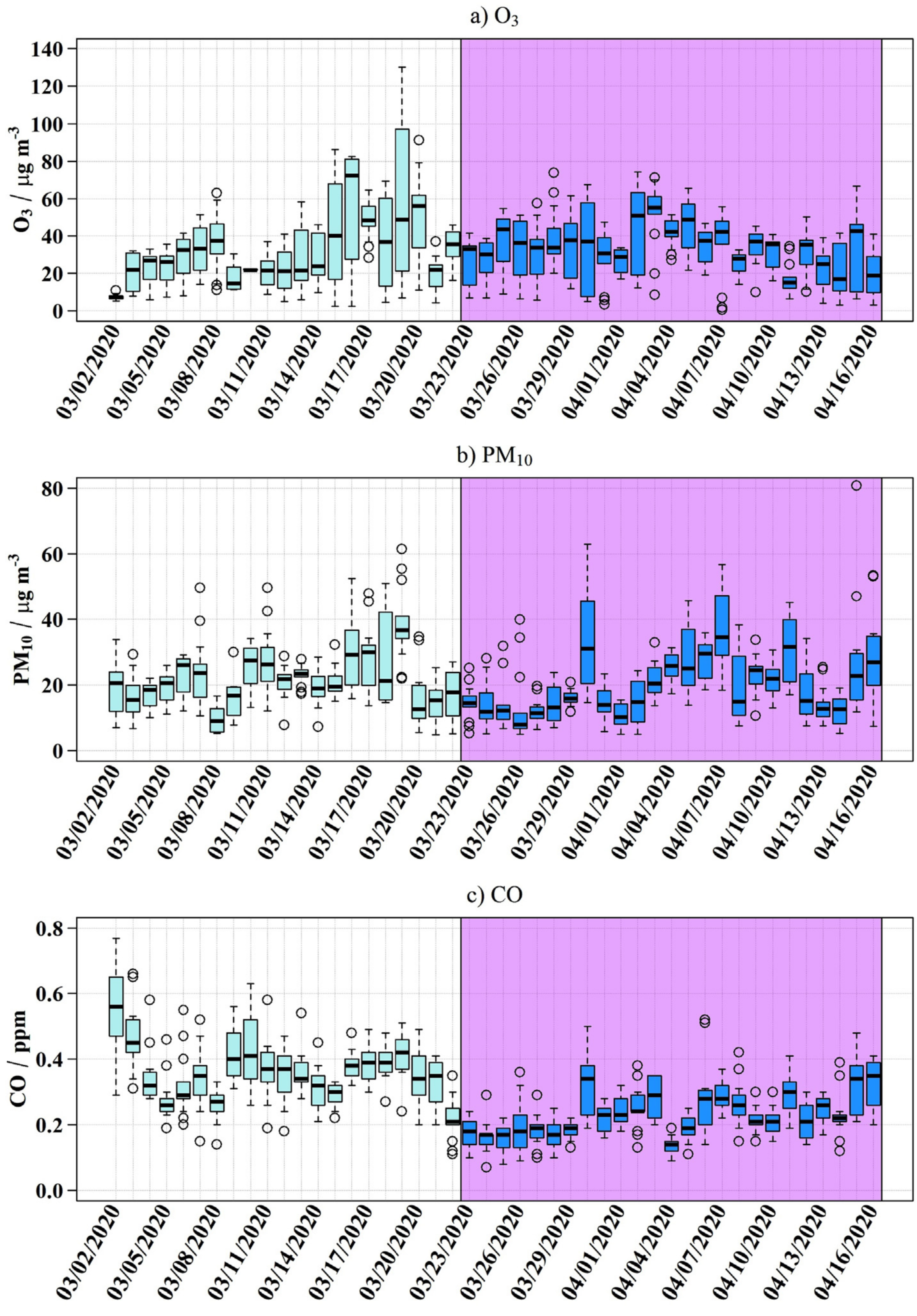


**Fig. 4.** Concentration values determined at Tijuca monitoring station from March 2 to April 16, 2020. a) $O_3$ (μg m$^{-3}$); b) $PM_{10}$ (μg m$^{-3}$); c) CO (ppm). The lockdown began on March 23, 2020.

In order to clarify these results, data were classified and analyzed for each week. The primary pollutants $PM_{10}$, $NO_2$ and CO concentrations determined from March 2 to April 12, 2020 are shown in Figs. 5–7. Data are presented as boxplots grouped in weeks: first (03/02–03/08), second (03/09–03/15), third (03/16–03/22), fourth (03/23–03/29), fifth (03/30–05/04) and sixth (05/04–12/04). The beginning of each "week" was considered as being on Mondays to match the implementation of the main restrictions. For each period, 1-hour means, from 6:30 to 18:30 h (local time BRT), were calculated and plotted in Figs. 5–7. Results covering the whole day (day and night hours) are shown in the Supplementary material section (Figs. S4–S6).

The first two weeks in March (from March 2 to March 15) were used as a reference. As previously described, on March 16 (third week in Figs. 5–7) schools and universities were closed and social isolation was recommended. When considering the primary pollutant $PM_{10}$, it was observed an increase in the concentrations (median values) determined in Irajá (10.7%) and Tijuca (11.0%) in the third week in comparison with the values for March 2–March 15. If data were compared with a longer period (02/16/2020–03/15/2020) the difference is still higher (approximately 25–30%) because of the heavy rains in February which led to lower particulate matter levels. Concentrations levels in Bangu were lower in the third week in comparison to the second.

For $NO_2$, concentrations (median values) in the third week were 28.8% higher and 1.8% lower in Irajá, and Bangu, respectively. If data for a longer period (02/16/2020–03/15/2020) were used as comparison, the difference is higher (approximately 10–20% higher). For CO, values were 15.2% lower and 12% higher in Bangu and Tijuca, respectively. The increase in primary pollutant levels in Irajá and Tijuca can be

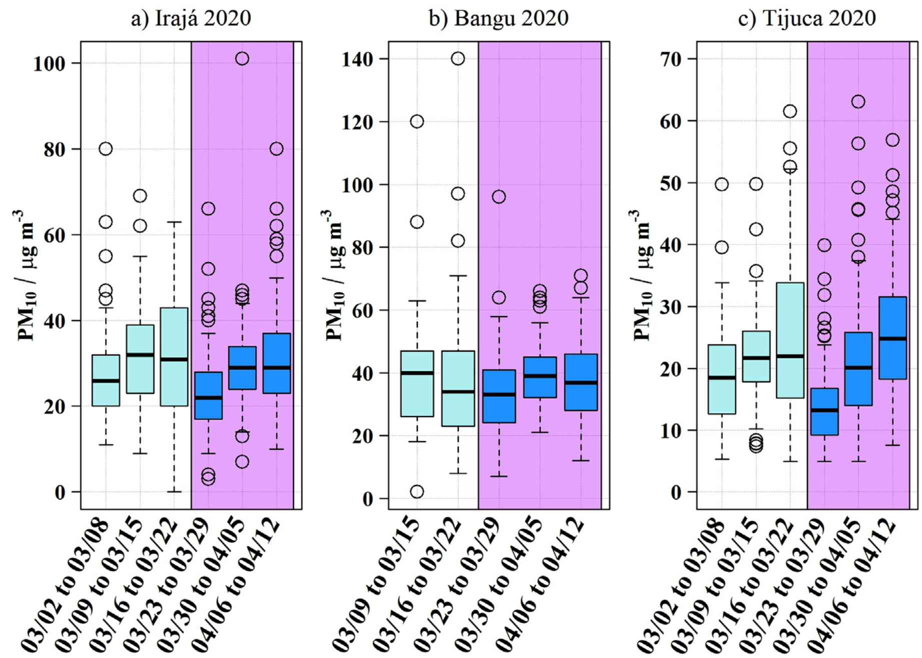


**Fig. 5.** Concentration values of $PM_{10}$ (μg $m^{-3}$) determined at a) Irajá, b) Bangu and c) Tijuca monitoring station from March 2 to April 12, 2020. $PM_{10}$ concentrations were not determined from March 2 to March 8 in Bangu.

attributed to the small reduction in the traffic and people circulation in the city. Meteorological conditions as a high atmospheric pressure system, high temperatures and absence of rains until March 20 could contribute to the increase in pollutant concentrations. Winds from the north-northwest also favored the transport of pollutants to Irajá and Tijuca. As an example, air masses arriving in Irajá were simulated using the dispersion model Hysplit implemented by the *Air Resources Laboratory* - NOAA e *Australian Bureau of Meteorology* (HYSPLIT, 2020; Rolph et al., 2017). Using a backward dispersion model, air masses arriving at 8:00 (local time, BRT) from the north-northwest were modelled (Fig. S7 Supplementary Material). The air mass trajectory passed through the industrial areas of Nova Iguaçú and Belford Roxo and over the main highways BR-101 and 116, and also through several avenues and the expressways Linha Vermelha and Avenida Brasil, with intense

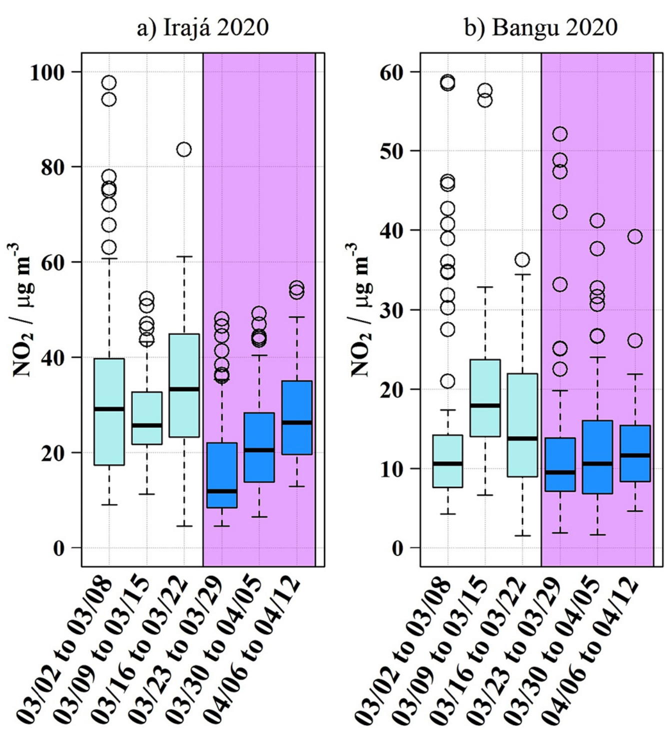


**Fig. 6.** Concentration values of $NO_2$ (μg $m^{-3}$) determined at a) Irajá and b) Bangu monitoring station from March 2 to April 12, 2020. $NO_2$ concentrations were not determined in Tijuca.

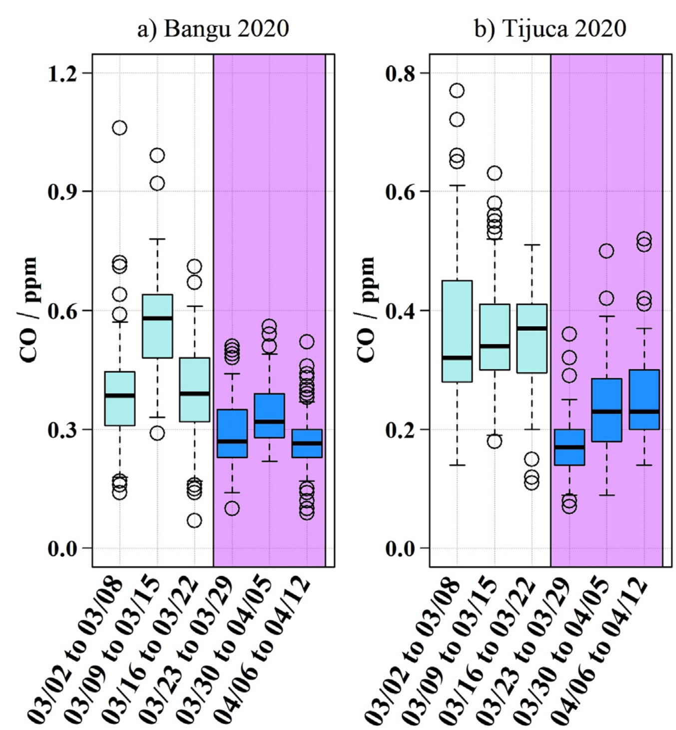


**Fig. 7.** Concentration values of CO (ppm) determined at a) Bangu and c) Tijuca monitoring station from March 2 to April 12, 2020. CO concentrations were not determined in Irajá.

**Table 2**
Variations (%) of $PM_{10}$ (μg $m^{-3}$), $NO_2$ (μg $m^{-3}$), $O_3$ (μg $m^{-3}$) and CO (ppm) concentrations during the lockdown, relative to March 2–15, 2020 (first and second weeks), third (03/16–03/22), fourth (03/23–03/29), fifth (03/30–05/04) and sixth (05/04–12/04) weeks.

| Station | Third week (03/16–03/22), partial restrictions | Fourth week (03/23–03/29), lockdown | Fifth week (03/30–05/04), lockdown | Sixth week (05/04–12/04), lockdown |
|---|---|---|---|---|
| $PM_{10}$ | | | | |
| Bangu | −15.0 | −17.5 | 2.5 | 7.5 |
| Irajá | 10.7 | −21.4 | 3.6 | 3.6 |
| Tijuca | 11.0 | −33.3 | 2.1 | 25.5 |
| $NO_2$ | | | | |
| Bangu | −1.8 | −32.2 | −32.1 | −16.8 |
| Irajá | 28.8 | −53.9 | −19.7 | 1.4 |
| $O_3$ | | | | |
| Bangu | 33.5 | −2.7 | 17.0 | −7.8 |
| Irajá | 31.1 | 12.9 | 23.7 | −2.7 |
| Tijuca | 63 | 44.0 | 67.1 | 34.0 |
| CO | | | | |
| Bangu | −15.2 | −41.3 | −30.4 | −42.4 |
| Tijuca | 12 | −48.5 | −30.3 | −30.3 |

traffic of both light and heavy-duty vehicles. The monitoring station of Bangu, located in the west area (see Fig. 1), between the massifs of Pedra Branca and Gericinó-Mendanha, received winds from the west area and was not impacted by the vehicular emissions of the main avenues and highways.

On March 23, the partial lockdown was implemented with a high initial response of the population. A clear decrease of $PM_{10}$ and $NO_2$ was observed in all the stations as a consequence of a decrease of approximately 80% in the vehicular flux (Cyberlab, 2020). The reduction in $PM_{10}$ levels (median values) in comparison with the first two weeks (shown in Fig. 5) was 21.4, 17.5 and 33.3% for Irajá, Bangu and Tijuca, respectively. For $NO_2$ (Fig. 6), was 53.9 and 32.2% for Irajá and Bangu, respectively. The reduction in CO concentrations was 48.5 and 41.3% in Tijuca and Bangu, respectively (Fig. 7).

As expected, the decrease in $PM_{10}$ and $NO_2$ was not directly proportional to the vehicular flux reduction, because it depends on other factors such as the transport of air masses and meteorological parameters. Moreover, the traffic of trucks and other cargo vehicles was not reduced since supermarkets, drug and construction materials stores continued the activities as well as industries and gasoline stations. These vehicles fueled with diesel are the main contributors to $PM_{10}$ and $NO_2$. Urban buses circulation was only partially reduced (approximately 50%). Considering the last emission inventory for the MRRJ (INEA, 2016) emissions of $PM_{10}$ and $NO_2$ are mainly due to heavy-duty vehicles. Trucks contribute to 49.8 and 32.1% of $PM_{10}$ and $NO_2$ emissions, respectively, while urban buses account for 42.6 and 50.6%. The lower decrease for particulate matter levels in comparison to $NO_2$ is probably due to the highest contribution of trucks which continue circulating within the city. Other sources such as construction works, industrial emissions, dust resuspension and transport from the vegetated areas (rainforest) could also contribute to particulate matter emission. Recently, Tobias et al. (2020) reported similar results for the city of Barcelona (Spain). The decrease in CO levels was lower than the reduction of light-duty vehicles flux. In part, these results may be due to a surge in demand for food and package delivery services which led to the increase in motorcycles use.

On April 3, and during the weekend (April 4 and 5), an increase on vehicular flux was observed. As fully published in media, some gatherings were registered in supermarkets, banks and other public places, in part due to the payment of salaries, and also by the lack of consensus about the importance and need of social distancing and lockdown. As consequence $PM_{10}$, $NO_2$ and CO levels increased in comparison with the previous week. In Fig. S7 (Supplementary Material), air masses from the west, originating in an urban area, are shown for March 4.

In Table 2, the trends in primary pollutant levels are presented for the third to sixth weeks using March 2–15 as a reference. In general, as shown in Figs. 2–4, primary pollutants concentrations were lower on Sundays. However, since median values were used, the inclusion of Sundays had a negligible impact on values presented in Table 2. As shown in Figs. S4–S6 (Supplementary Material), when considering the night-time hours, the same trends were observed.

In Fig. 8, concentrations of $O_3$ (1-hour mean), the main secondary pollutant, determined at Irajá, Bangu and Tijuca monitoring station from March 2 to April 12, 2020 are displayed. In the Supplementary material section, data covering the whole day (day and night hours) are shown (Fig. S8).

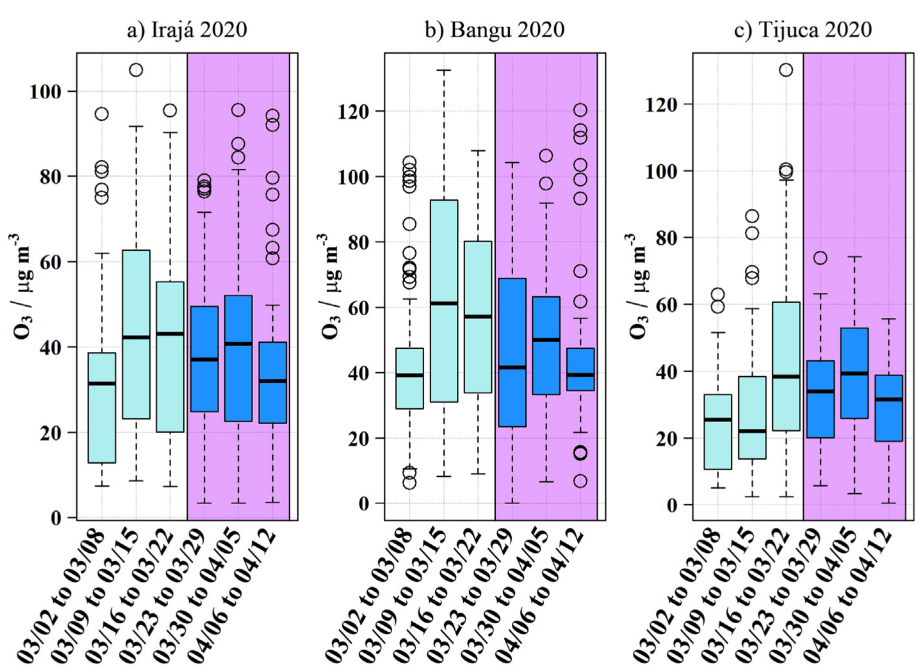


**Fig. 8.** $O_3$ concentrations (μg $m^{-3}$) determined at a) Irajá, b) Bangu and c) Tijuca monitoring station from March 2 to April 12, 2020.

As shown in Table 2, ozone levels increased in the three monitoring station during the third week in comparison with the two reference weeks (median values) by 31.1, 22.5 and 63.0% for Irajá, Bangu and Tijuca, respectively. After March 23, concentrations remained high. During the fourth week, in Irajá and Tijuca, values were 12.9 and 44.0% higher than values determined from March 2 to March 15. In Bangu, concentrations were only 2.7% lower. The same tendencies were observed in the following weeks. From April 6 to April 12, sparse rainfall and low solar irradiances favored the decrease on ozone levels. Similar results were also observed in Barcelona (Tobias et al., 2020).

As fully discussed in previous studies (Dantas et al., 2019, 2020), ozone concentrations in Rio de Janeiro highly depend on non-methane hydrocarbons (NMHC) and total nitrogen oxides ($NO_x = NO + NO_2$) concentrations ratios ($NMHC/NO_x$). THC and NMHC were only determined at Irajá and Bangu monitoring stations. Obtained values are shown in Figs. S9–S12 (Supplementary Material).

Results showed that, in Irajá, NMHC concentrations increased in the third week (21.4%) and with the lockdown decreased 28.4 and 14.3% (fourth and fifth weeks, respectively) and in April increased again. Since $NMHC/NO_x$ ratios were approximately equal in the period of March 02–22, the increase in ozone concentrations was probably related to air masses entering from the northern industrial area. As recently discussed by Dantas et al. (2020), the reactivity of the volatile organic compounds (VOC) mixture in Irajá is highly increased by industrial air masses rich in aromatic compounds (such as alkyl-substituted benzene and xylene isomers). During the fourth and fifth weeks, the sharp decrease in $NO_2$ concentrations (53.9 and 19.7%, respectively) lead to an increase in ozone, since atmospheric chemistry in Rio de Janeiro is under VOC-controlled conditions. In April, as previously discussed, the levels of all pollutants had a small variation due to the relaxation of social isolation measures. In Bangu, NMHC remained with small variations and the increase of ozone levels may be attributed to the decrease in nitrogen oxides (Geraldino et al., 2020).

In order to perform a further analysis, the primary pollutants $PM_{10}$, $NO_2$ and CO concentration values determined from March 23 to April 12, 2020 (partial lockdown) were compared with the same values obtained in 2019. Results for the three studied locations are shown in Figs. S13–S15 (Supplementary Material). In these figures, individual 1-hour values for each day were used to construct the boxplots.

For $PM_{10}$, median values for 2020, were equal, 19.35% higher and 28.70% lower than in 2019 for Irajá, Bangu and Tijuca, respectively. For $NO_2$, median values were lower in 2020: 32.9 and 24.1% in Irajá and Bangu, respectively. CO were also lower in 2020: median values 37.0% and 43.6% in Bangu and Tijuca, respectively.

These results are in general agreement with the former analysis. Particulate matter emissions are mainly related to diesel fuel and also industrial and construction work which were affected to a lesser extent by the lockdown. Furthermore, local characteristics, such as the distribution of the fleet and transport of air masses could influence the results: in Tijuca, a residential area where the main input is due to vehicular emissions, $PM_{10}$ levels decreased. Bangu receives the input of air masses originating in Santa Cruz and Campo Grande, where are located several metallurgical and steel industries and also mining and construction business which could contribute to particulate matter increase.

In spite of $NO_2$ being emitted mostly by diesel vehicles, levels were lower in 2020, as was observed in other countries and could be probably attributed to the decrease in local and interstate buses circulation, massive cancellations of flights and cruises and the reduce demand of energy production. The CO sharp decrease is clearly related to the emission reduction as a consequence of a 50–80% decrease in light-duty vehicular flux.

## 4. Conclusions

These results showed the impact of the partial lockdown on the air quality of the city of Rio de Janeiro. The main restrictions were applied from March 23, however, in April, social isolation was relaxed in spite of the recommendations of WHO, scientist and medical experts and also state's governments. The partial confinement of the population, reduction of road traffic and economic activity led to the decrease in CO and $NO_2$ levels and, by contrast, to the increase in ozone concentrations. Similar results had been observed in 2018, during a 10-day truck driver strike. Since particulate matter and ozone are, in general, the pollutants of main concern in Rio the Janeiro, these results suggest that the assessment of air quality policies in the city requires the analysis of air masses transported from the industrial areas as well as the study of VOC speciation and the impact of $NMHC/NO_x$ ratios on ozone levels, considering that the high temperatures and solar radiation indexes favor ozone formation. The impact of meteorological conditions cannot be neglected and should be analyzed in the future.

## CRediT authorship contribution statement

**Guilherme Dantas:** Software, Validation, Formal analysis, Investigation, Writing - review & editing. **Bruno Siciliano:** Software, Validation, Formal analysis, Investigation, Writing - review & editing. **Bruno Boscaro França:** Data curation, Validation, Writing - review & editing. **Cleyton M. da Silva:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing. **Graciela Arbilla:** Conceptualization, Investigation, Formal analysis, Writing - original draft, Writing - review & editing, Resources, Supervision.

## Declaration of competing interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.139085.

## References

Alerta Rio, 2020. Sistema Alerta Rio da Prefeitura do Rio de Janeiro. http://alertario.rio.rj.gov.br/ (accessed April 02 2020).

Argentina, 2020. Ministerio de Salud. https://www.argentina.gob.ar/coronavirus/informe-diario (accessed March 31 2020).

Braga, A.L., Siciliano, B., Dantas, G., André, M., da Silva, C.M., Arbilla, G., 2019. Levels of volatile carbonyl compounds in the Atlantic rainforest, in the city of Rio de Janeiro. Bull. Environ. Contam. Toxicol. 102, 757–762.

CONAMA, 1990. Resolução CONAMA 03/1990. http://www2.mma.gov.br/port/conama/legiabre.cfm?codlegi=100 (accessed April 10 2020).

CONAMA, 2018. Resolução CONAMA 491/2018. http://www2.mma.gov.br/port/conama/legiabre.cfm?codlegi=740 (accessed April 10 2020).

Copernicus, 2020. https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/copernicus-sentinel-5p (accessed April 15 2020).

Croda, J., Oliveira, W.K., Frutuoso, R.L., Mandetta, L.H., Silva, D.C.B., Brito-Sousa, J.D., Monteiro, W.M., Lacerda, M.V.G., 2020. COVID-19 in Brazil: Advantages of a Socialized Unified Health System and Preparation to Contain Cases. https://doi.org/10.1590/0037-8682-0167-2020.

Cyberlab, 2020. Dados de contagem veicular. https://twitter.com/cyberlabsai?ref_src=twsrc%5Egoogle%7Ctwcamp%5Eserp%7Ctwgr%5Eauthor (accessed April 10 2020).
Dantas, G., Siciliano, B., Freitas, L., Seixas, E.G. de, da Silva, C.M., Arbilla, G., 2019. Why did ozone levels remain high in Rio de Janeiro during the Brazilian truck driver strike? Atmos. Pollut. Res. 10, 2018–2029.
Dantas, G., Siciliano, B., da Silva, C.M., Arbilla, G., 2020. A reactivity analysis of volatile organic compounds in a Rio de Janeiro urban area impacted by vehicular and industrial emissions. Atmos. Pollut. Res. 11, 1018–1027.
DOERJ, 2020. Diário Oficial do Estado do Rio de Janeiro (DOERJ). Decreto N° 46.980 de 19 de março de 2020. https://www.legisweb.com.br/legislacao/?id=391093 (accessed April 17 2020).
Earth, 2020. An animated map of global wind and weather. http://earth.nullschool.net (accessed April 17 2020).
Fiocruz, 2020. Agência Fiocruz. Monitora COVID-19 alerta para o aumento da circulação nas ruas. https://agencia.fiocruz.br/monitoracovid-19-alerta-para-aumento-de-circulacao-nas-ruas (accessed April 17 2020).
Geraldino, C.G., Arbilla, G., da Silva, C.M., Corrêa, S.M., Martins, E.M., 2020. Understanding high tropospheric ozone episodes in Bangu, Rio de Janeiro, Brazil. Environ. Monit. Assess. 192, 156. https://doi.org/10.1007/s10661-020-8119-3.
Hopkins, John, 2020. John Hopkins University of Medicine. Coronavirus Research Center, p. 20. https://coronavirus.jhu.edu/map.html (accessed April 17 2020).
HYSPLIT, 2020. NOAA air resources laboratory. https://www.ready.noaa.gov/HYSPLIT.php.
IBGE, 2020. Brazilian cities. https://cidades.ibge.gov.br/brasil/rj/rio-de-janeiro/panorama (accessed April 17 2020).
INEA, 2016. Inventário Emissões de Fontes Veiculares. http://www.inea.rj.gov.br/wp-content/uploads/2019/01/Invent%C3%A1rio-de-Emiss%C3%B5es-de-Fontes-Veiculares.pdf (accessed April 17 2020).
Mendes, D., Dantas, G., Da Silva, M.A., De Seixas, E.G., Da Silva, C.M., Arbilla, G., 2020. Impact of the petrochemical complex on the air quality of an urban area in the city of Rio de Janeiro, Brazil. Bull. Environ. Contam. Toxicol. 104, 438–443.
Muhammad, S., Long, X., Salman, M., 2020. COVID-19 pandemic and environmental pollution: a blessing in disguise? Sci. Total Environ., 138820 https://doi.org/10.1016/j.scitotenv.2020.138820 Online April 20.
NASA, 2020. Earth observatory. National Aeronautics and Space Administrationhttps://earthobservatory.nasa.gov/images/146362/airborne-nitrogen-dioxide-plummets-over-china (accessed April 17 2020).
NEI, 2014. Inventário Nacional de Emissões Atmosféricas por Veículos Automotores Rodoviários. http://www.antt.gov.br/backend/galeria/arquivos/inventario_de_emissoes_por_veiculos_rodoviarios_2013.pdf (accessed April 02 2020).
R, 2020. https://www.r-project.org/ (accessed April 02 2020).
Rodriguez-Morales, A.J., Gallego, V., Escalera-Antezana, J.P., Méndez, C.A., Zambrano, L.I., Franco-Paredes, C., Suárez, J.A., Rodriguez-Enciso, H.D., Balbin-Ramon, G.J., Savio-Larriera, E., Risquez, A., Cimerman, S., 2020. COVID-19 in Latin America. The implications of the first confirmed case in Brazil. Travel Med. Infec. Dis., 101613 https://doi.org/10.1016/j.tmaid.2020.101613 29 February 2020.
Rolph, G., Stein, A., Stunder, B., 2017. Real-time Environmental Applications and Display sYstem: READY. Environ. Model. Softw. 95, 210–228.
Saadat, S., Rawtani, D., Hussain, C.M., 2020. Environmental perspective of COVID-19. Sci. Total Environ. 728, 138870. https://doi.org/10.1016/j.scitotenv.2020.138870.
Silva, C.M., Silva, L.L. da, Corrêa, S.M., Arbilla, G., 2018. A minimum set of ozone precursor volatile organic compounds in an urban environment. Atmos. Pollut. Res. 9, 369–378.
Tobias, A., Carnerero, C., Reche, C., Massagué, J., Via, M., Minguillón, M.C., Alastuey, A., Querol, X., 2020. Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. Sci. Total Environ. 726, 138540. https://doi.org/10.1016/j.scitotenv.2020.138540.
Tsuruta, F., De Carvalho, N., Da Silva, C., Arbilla, G., 2017. Air quality indexes in the city of Rio de Janeiro during the 2016 Olympic and Paralympic games. J. Braz. Chem. Soc. 29, 1291–1303.
WHO, 2020a. World Health Organization. Novel coronavirus (2019-nCoV). http://www.euro.who.int/en/health-topics/health-emergencies/novel-coronavirus-2019-ncov_old (accessed April 02 2020).
WHO, 2020b. World Health Organization. WHO director-general's opening remarks at the media briefing on COVID-19 - 11 March 2020. https://www.who.int/dg/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19—11-March-2020.